

A simulation-based assessment of Community-Based Energy Trading for circular energy sharing in low-income communities

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ARTICLE INFO

Dataset link: <http://dx.doi.org/10.17632/nm2vc4v2br.1>

Keywords:

Decentralised energy systems

Battery energy storage

Demand-side management

Energy equity

Renewable energy utilisation

Techno-economic modelling

ABSTRACT

The growing adoption of decentralised renewable energy, particularly solar photovoltaic (PV) systems, presents opportunities to advance low-carbon development and circular economy objectives. However, unequal policy frameworks, infrastructure availability, and socio-economic conditions continue to limit equitable outcomes, especially in under-resourced communities. This study presents a simulation-based proof-of-concept evaluation of a Community-Based Energy Trading (CBET) framework designed to operationalise energy circularity within low-income communities through local energy redistribution. The proposed CBET model centres on a public school equipped with solar PV generation acting as a single prosumer that redistributes surplus electricity to nearby households using rule-based energy allocation rather than optimisation-based control. Using empirical electricity demand data for one school and five households in Cape Town, South Africa, two system configurations are simulated: CBET without household battery storage and CBET with battery-enabled households. Performance is evaluated in terms of local renewable energy utilisation, household electricity cost reductions, and peak-period grid demand. Results indicate that CBET increases local solar energy reuse efficiency to approximately 90% and reduces household reliance on grid electricity by up to 16% when battery storage is included. In addition, peak-hour demand is reduced by 13%, contributing to improved grid stability, energy equity, waste minimisation, and community-level resilience. These findings demonstrate that meaningful techno-economic benefits can be achieved through simplified community-level energy sharing arrangements without complex market mechanisms. However, the results are contingent on the assumed demand profiles and the single case configuration analysed. The study positions CBET as a feasible proof-of-concept for community-scale circular energy sharing systems operating under local capacity and policy constraints in the Global South.

1. Introduction

The global energy landscape is transforming under the urgent need to cut greenhouse gas emissions, decentralise power systems, and promote equitable access to clean energy. Distributed energy resources (DERs) have emerged as a central component of this transition, enabling the localisation of the generation and consumption of renewable energy [1,2]. While decentralisation offers technical and environmental benefits, its deployment has frequently prioritised market efficiency and technological readiness, often overlooking the socio-economic and infrastructural realities of low-income communities, especially in the Global South. In many developing regions, where infrastructure remains fragile and inequality high, decentralised energy models must be contextually adapted to ensure technical feasibility, social equity, and long-term resilience [3–6]. As a result, the benefits of

decentralised energy systems remain unevenly distributed, reinforcing existing inequalities in energy access and affordability.

In parallel, the concept of the circular economy has gained prominence as a framework for reducing waste, extending resource lifecycles, and maximising local value creation [7,8]. In energy systems, circularity emphasises the local reuse of renewable generation and the retention of social and economic value alongside technical efficiency [9,10]. Decentralised renewable energy systems are well-positioned to operationalise these principles by enabling energy to circulate within bounded communities rather than being exported to centralised grids. However, translating circular economy concepts into practical energy-sharing mechanisms remains an open challenge, particularly in under-resourced settings where financial capacity, digital infrastructure, and

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List of Abbreviations

CBET	Community-Based Energy Trading
DER	Distributed Energy Resources
DoD	Depth of Discharge
DSM	Demand-Side Management
EUI	Energy Use Intensity
kWh	Kilowatt-hour
kWp	Kilowatt-peak
MSC	Maximizing Self-Consumption
P2P	Peer-to-Peer
PV	Photovoltaic
SOC	State of Charge
TOU	Time-of-Use
URB	Unified Rule-Based

regulatory support are limited [11–13]. In this study, circular economy principles are operationalised through a combination of three interrelated dimensions: local energy looping [14], socio-economic redistribution [15], and productive reuse of existing infrastructure [16]. Together, these dimensions frame circularity as a system-level process of value retention through local reuse, reduced waste, and shared access to resources within decentralised energy systems [14–18]. They are operationalised through specific evaluation metrics and simulation design choices described in Section 2.

Renewable energy systems, particularly solar photovoltaic (PV), have become pivotal in expanding clean energy access, especially across Sub-Saharan Africa with its high solar irradiance [2]. The rise of small-scale generation has created a new class of energy users known as prosumers, entities that both produce and consume energy [1]. Their emergence supports the shift toward decentralised and democratised energy markets, moving beyond traditional centralised grids. Peer-to-peer (P2P) energy trading has consequently gained traction as an innovative mechanism for redistributing surplus solar energy among prosumers [1,19]. Supported by policies such as feed-in tariffs and net metering, P2P systems allow producers to offset energy costs and supply power back to the grid. Over 70 countries have implemented mandatory net metering policies, allowing greater participation in decentralised energy generation [1]. Beyond direct benefits to producers and consumers, energy trading reduces peak demand, alleviates grid stress, and improves the general reliability of the system [20]. Research on decentralised trading has diversified from early game-theoretic, optimisation, and auction-based models [19,21,22] to include blockchain, simulation, and platform-based systems [1]. [22] designed microgrids enabling direct peer exchange in off-grid and grid-constrained regions, while [19] introduced the concept of a federated power plant, where prosumers collectively manage distributed resources to enhance bargaining power and grid participation. Studies in Nepal and Morocco demonstrated how P2P and peer-to-grid (P2G) strategies can enhance resilience, reduce grid reliance, and boost community income [23,24]. Collectively, these studies underscore the value of energy trading systems that maximise local energy use, support grid stability, and adapt to regional socio-economic conditions, core principles of the circular economy. However, the existing literature mainly focuses on P2P frameworks that assume high technological readiness, financial capacity, and supportive policy environments, conditions that are often absent in developing contexts. To address these limitations, alternative decentralised energy-sharing models that prioritise collective benefit and infrastructural simplicity are required. In this context, Community-Based Energy Trading (CBET) offers a complementary paradigm to conventional P2P trading. Rather than enabling bilateral trading among individual prosumers, CBET centres energy generation at a shared

institutional node and redistributes surplus renewable energy to surrounding consumers within the same socio-economic ecosystem. This structure reduces transaction complexity, lowers entry barriers for low-income households, and aligns energy sharing with principles of social equity and circular resource use.

Limited research has examined decentralised energy sharing models in South Africa (SA) [25], highlighting the need for further investigation. [26] developed a grid-integrated hybrid P2P renewable energy-based electric vehicle charging system, demonstrating how energy trading can reduce costs during periods of abundant renewable supply. Similarly, [25] proposed a P2P energy sharing model enabling prosumers to buy and sell wind and solar power in real time, optimising energy use and reducing grid dependence. Despite policy reforms aimed at liberalising the electricity sector and promoting renewable energy since the late 1990s, the national grid in SA remains highly centralised, carbon-intensive, and vulnerable to supply disruptions [12,27]. These challenges disproportionately affect low-income communities and public institutions such as schools, which frequently experience unreliable electricity supply and constrained infrastructure investment. The disparities are embedded in South Africa's public school quintile (Q1–Q5) classification, which mirrors the socio-economic status of their surrounding communities. Quintile 1 (Q1) schools – at the lowest end of the scale – serve South Africa's most under-resourced communities, often facing poor infrastructure and unreliable grid access, while Q5 schools in affluent areas benefit from stable electricity and better facilities [28]. Although the quintile system aims to promote equity through targeted funding, many Q1 schools remain constrained by infrastructural deficits and limited capacity for renewable investment. Nevertheless, these institutions hold significant potential for energy circularity. Their physical space, central role in communities, and access to public funding position them as ideal community prosumers – local generators and redistributors of renewable energy. Leveraging schools as decentralised energy hubs offers a promising pathway for regionally grounded, socially equitable low-carbon transitions in South Africa and other developing regions.

Building on these observations, this study presents a Community-Based Energy Trading (CBET) model that integrates energy circularity and social equity in under-resourced settings. In this model, a solar-powered school functions as a prosumer, sharing surplus energy with nearby low-income households to redistribute clean power within the same socio-economic ecosystem. Unlike conventional P2P systems, CBET centralises generation and prioritises community benefit over market efficiency, transforming schools into active energy hubs that embody circular principles of reuse, regeneration, and shared value creation. By reducing infrastructure needs, the CBET framework enhances financial feasibility for low-income regions. Results are interpreted through a context-specific circular economy lens, showing how local infrastructure, storage capacity, and policy conditions shape energy flows and equity outcomes. CBET serves as an illustrative analytical framework for adaptive policy and infrastructural design, illustrating how community-led systems can advance equitable low-carbon transitions.

The contribution of this paper is threefold. First, it develops and evaluates a simulation-based, proof-of-concept CBET model that differs from conventional P2P trading by centring energy redistribution around a single institutional prosumer and employing rule-based energy allocation rather than optimisation-driven market mechanisms. This design explicitly targets low-income contexts with limited technological, financial, and regulatory capacity. Second, the study demonstrates – through empirical demand-driven simulation – how a public institution, specifically a solar-powered school, can function as a community energy anchor, enabling local renewable energy reuse and peak-demand mitigation without requiring household-level PV ownership. This provides a concrete system architecture that extends existing decentralised energy trading literature beyond multi-prosumer market designs. Third, using a case study from South Africa, the paper quantifies the techno-economic and system-level impacts of CBET

under constrained conditions, showing how simplified community energy sharing can improve local energy utilisation, reduce household grid dependence, and enhance peak-load management. Together, these contributions position CBET as a context-sensitive proof-of-concept framework for circular energy sharing in low-income communities.

The paper is organised as follows: Section 2 outlines the methodology; Section 3 presents the results and discussion for both configurations; and Section 4 concludes with implications for circular economy strategies and directions for future research on context-sensitive energy trading models.

2. Methodology

This study employs a simulation-based evaluation approach to examine the behaviour of a CBET system under predefined operational rules and realistic constraints. The objective is not to mathematically optimise system parameters, control strategies, or market outcomes, but to analyse how alternative system configurations influence energy flows, household electricity costs, and grid interaction using empirical demand data. Simulation is therefore used as a controlled experimental tool to enable consistent comparison across configurations, following established approaches in decentralised energy system assessment [29].

Two CBET configurations are analysed. In both cases, a public school functions as a single institutional prosumer equipped with solar PV generation. In the first configuration, surrounding households rely exclusively on grid electricity. In the second configuration, households are equipped with battery storage systems (BSS) that enable temporal shifting of energy received through CBET. Households with PV are intentionally excluded, as high levels of self-sufficiency would reduce reliance on shared energy resources and obscure the evaluation of community-level energy redistribution.

2.1. Circular economy framing and operationalisation

Circular economy principles provide the analytical framework for evaluating CBET system performance, operationalised through measurable system, household, and infrastructure-level indicators. Rather than treating energy exchange solely as a technical or economic process, circularity is conceptualised as a system property arising from the circulation of renewable energy, infrastructure, and economic value within a bounded community. This study draws from established circular economy scholarship that emphasises value retention, shared access, and system-level resource looping in energy systems, rather than material recycling or lifecycle optimisation, which fall outside the scope of this study.

In this study, circularity is operationalised through three interrelated dimensions: local energy looping, socio-economic redistribution, and productive reuse of existing infrastructure. These dimensions guide both the selection of evaluation metrics and the interpretation of simulation outcomes, ensuring that system performance is assessed not only in terms of efficiency but also through equity and context-sensitive considerations. Accordingly, the analysis focuses on how renewable energy is retained within the community, how energy-related economic benefits are distributed to non-generating households, and how existing public infrastructure can function as an energy anchor without requiring widespread household-level asset ownership.

2.2. Data and case study

2.2.1. Case study

The case study is situated in Cape Town, South Africa, a municipality that has implemented progressive policies enabling embedded generation and municipal feed-in tariffs [30]. These regulatory conditions support the adoption of decentralised renewable energy while maintaining grid stability, making the region a suitable testbed for

community-based energy sharing initiatives. This municipal policy incentivises local solar adoption, allows residents to offset energy costs, and demonstrates the city's commitment to decentralised renewable energy. By balancing grid stability with sustainable energy production, Cape Town provides a supportive regulatory environment for community-based trading initiatives.

2.2.2. Dataset and data processing

Data were collected from two primary sources. First, electricity usage data for 53 public schools in the Western Cape, South Africa, were obtained from smart meters covering December 2022 to November 2023, processed following the methodology of [31]. Second, household consumption data were drawn from the Domestic Electrical Load Metering (DELM) database developed at the University of Cape Town [32]. The DELM data set provides hourly consumption readings for more than 1200 South African households, with continuous nine-month records (January–September 2014) representing typical residential usage patterns. A consumption-based grouping approach was used to match schools and households according to socio-economic status. Because direct income data were unavailable, energy use served as a proxy for income, with lower consumption associated with low-income households characterised by fewer appliances and lower overall demand. Data preprocessing occurred in two stages. First, schools were classified into low-, medium-, and high-usage categories based on total energy use percentiles [0, 0.25, 0.75, 1]. The same categorisation was applied to households in the DELM dataset. To reflect socio-economic alignment, schools and households were matched based on energy usage, consistent with South Africa's quintile classification system. For this study, five households from the low-usage group were matched with a low-income school, creating a representative case for analysing community-based energy trading dynamics.

2.3. Evaluation metrics

To evaluate the performance of the CBET model beyond conventional technical efficiency, this study adopts a circular economy-oriented evaluation framework based on three interrelated dimensions.

- 1. Energy Circularity Efficiency (Local Energy Looping):** Energy circularity efficiency is defined as the proportion of locally generated solar energy that is reused within the community rather than exported to the grid or curtailed. This metric quantifies the extent to which the CBET model closes local energy loops by retaining renewable energy within a bounded community before grid interaction.
- 2. Socio-Economic Redistribution (Household-Level Equity):** Socio-economic circularity is assessed through proportional reductions in household electricity costs relative to baseline grid dependence. These outcomes reflect the redistribution of renewable energy value to households without PV ownership and serve as an operational proxy for affordability and distributive equity within the community.
- 3. System Resilience and Infrastructural Circularity:** Productive reuse of existing infrastructure is operationalised through the system configuration in which a public school functions as a single institutional prosumer and community energy anchor. The effectiveness of this arrangement is interpreted through system-level outcomes, including reductions in peak-hour grid demand and improved load balancing, which indicate enhanced local resilience without requiring household-level generation assets.

All evaluation metrics are computed at an hourly temporal resolution and aggregated across defined TOU periods to enable consistent comparison between baseline and CBET configurations.

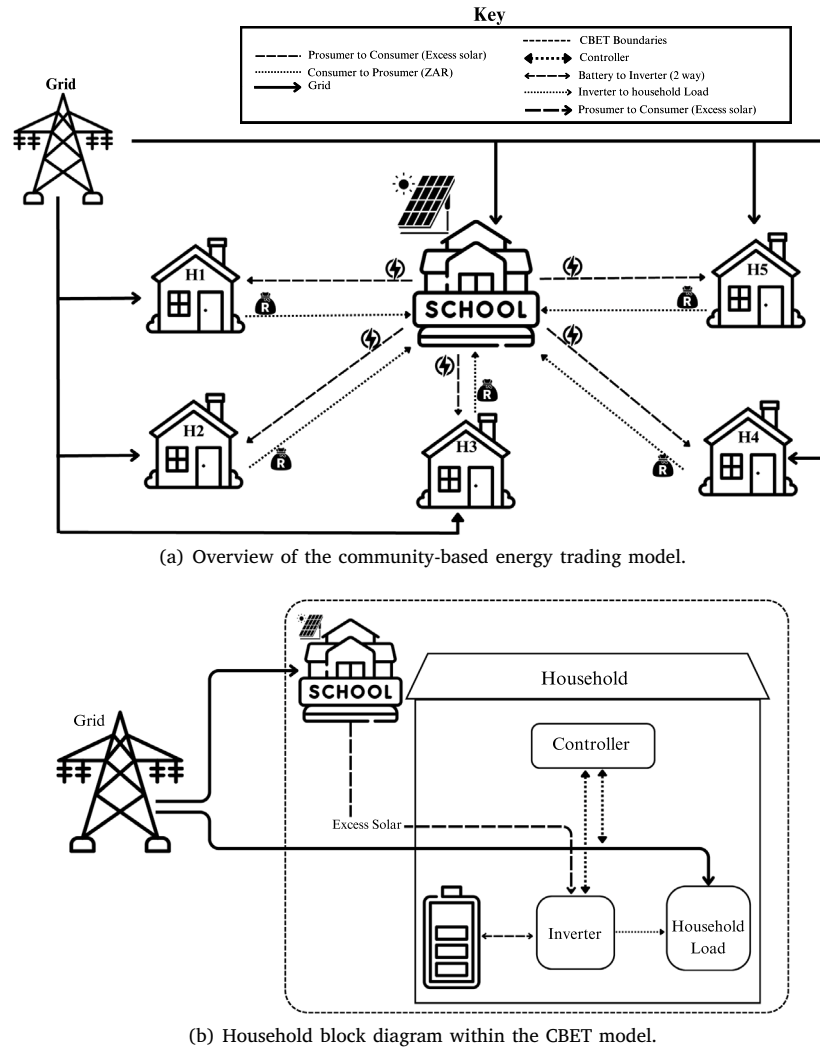


Fig. 1. System architecture of the CBET model. A public school acts as a central prosumer, supplying surplus solar energy to nearby low-income households while remaining grid-connected. Panel (a) illustrates the overall energy exchange structure, and panel (b) shows the internal energy flow within a household, highlighting the interaction between grid supply, battery storage, and solar energy trading. Attribution: Icons were sourced from Flaticon.com.

2.4. Simulation setup

The simulation is implemented in Python using an hourly time step over a nine-month period, consistent with the temporal resolution of the empirical demand datasets. The simulation models energy interactions between the grid, the school (prosumer), and five households under predefined operational rules. Custom functions govern power allocation, battery charging and discharging, surplus distribution, and grid interaction. No mathematical optimisation routines were employed. Instead, energy management follows deterministic, rule-based logic that prioritises local solar utilisation, equitable distribution, and grid reliability. The sizing of PV and battery systems followed the method proposed by [33], tailored for low-income schools

2.4.1. System architecture

The system architecture of the grid-connected CBET model is shown in Fig. 1, with a detailed data flow within each household illustrated in Fig. 1(b). A school acts as a prosumer, generating solar energy and selling surplus electricity to nearby low-income households, which draw power from the school or, when necessary, the central grid. Bidirectional connections between the school, households, and the grid enable flexible energy exchange. Each household's system integrates a grid connection, battery storage, an inverter, controller, and household

load, as well as access to surplus solar energy purchased from the school. The controller manages power distribution according to Algorithm 1, while the battery and inverter are omitted in the no-battery configuration.

2.4.2. Selection of optimal PV and battery sizing

The solar PV and battery sizes proposed by [33] were adopted for the school, as they correspond to the low-income category identified in this study. That work determined an optimal configuration for schools in similar socio-economic contexts, balancing self-sufficiency and grid independence. The recommended setup – a 15 kWp PV system paired with a 6 kWh battery – requires an initial investment of 226 000 ZAR (approx. \$12,600) and effectively supports both the school's energy needs and surplus generation for community trading.

For households, a 3 kWh battery was selected, consistent with average residential demand and sufficient to cover evening peak usage. This capacity enables households to store excess solar energy from the school and reduce grid dependence. The battery cost was estimated at 6000 ZAR (approx. \$670) per kWh, plus a fixed installation cost of 2000 ZAR (approx. \$112), including inverter integration.

2.4.3. Battery storage system modelling

During the simulation, the battery is subject to specific constraints to accurately model its performance under intermittent conditions. The maximum charge rate is limited to 0.5C, and the maximum discharge rate is 1C. The minimum state of charge (SOC) was set to 20%, and the initial SOC of the battery is configured to start at 50%, with the charging and discharge efficiencies set at 96%. These parameters are essential for simulating realistic battery behaviour, aligning performance with typical operational limits and efficiency rates observed in practical applications. Battery discharge in the CBET model follows a static, rule-based strategy where stored energy is released during predefined evening peak hours aligned with South Africa's national TOU tariff structure. This strategy was intentionally selected to reflect a simple and implementable control approach suitable for low-income contexts, where advanced forecasting, household-specific optimisation, or dynamic control infrastructure may not be available. The battery control logic is therefore not intended to maximise individual household performance, but to provide a consistent basis for comparing system behaviour across configurations.

2.4.4. Simulation process

Simulation Architecture Description

The simulation models a grid-connected community-based energy trading network comprising a *prosumer* (the school) and five *consumer* households. Each entity is interconnected, allowing direct trading between the school and households within a decentralised microgrid. This setup supports bidirectional energy flow, enabling both grid supply and local prosumer-to-consumer exchanges.

School (Prosumer) Setup

The school acts as the central prosumer, equipped with solar PV systems and battery storage. During peak sunlight hours, surplus solar energy is made available for sale to nearby households. When solar generation and storage are insufficient, the school draws electricity from the grid to maintain reliability.

Consumer (Household) Setup

Five low-income households are modelled as consumers without individual PV systems. Two configurations are simulated: (1) battery-enabled households, and (2) Non-battery-enabled households. The bidirectional link between the school and households enables consumers to access excess solar energy generated by the school.

Energy Flow and Grid Integration

The CBET network enables bidirectional energy movement between the grid, the school, and households. While primary exchanges occur between the school and households, grid integration ensures stability and supply reliability during periods of low renewable generation.

School Simulation

The simulation adapts the Unified Rule-Based (URB) algorithm from [33] to manage the school's grid, PV, and battery operations. The algorithm maximises self-consumption of solar energy and uses stored energy during peak or low-solar periods. It was enhanced to include trading logic, allowing the school to sell surplus energy to households based on availability and demand.

Household Simulation Setup and Energy Trading

A Household class models the energy balance for each of the five households, each with a unique demand profile. Surplus solar energy from the school is allocated proportionally to household demand, ensuring a fair and equitable distribution of available energy. This proportional trading mechanism fosters a balanced energy-sharing ecosystem within the community.

Household Simulation with Battery

In the battery-integrated configuration, each household is equipped with a 3kWh BSS. The batteries store surplus solar energy supplied

Algorithm 1 Household Battery Integration with Proportional Solar Distribution

```

1: Input: school_row (solar production and demand), household_demand
   (each household's demand), battery parameters (for each household),
   total_households (number of households)
2: Output: Energy distribution from solar, grid, and battery for each
   household
3: for time step do
4:   Initialise total_excess_solar  $\leftarrow$  school_row['excess_solar']
5:   Initialise each household's demand and battery parameters
6:   for household  $i$  in households do
7:     household_demand  $\leftarrow$  household_demand[i]
8:     energy_from_school_solar  $\leftarrow$  min(household_demand,
       total_excess_solar)
9:     remaining_demand  $\leftarrow$  household_demand - energy_from_school_solar
10:    total_excess_solar  $\leftarrow$  total_excess_solar - energy_from_school_solar
11:    if hour  $\leq 17$  then
12:      Non-Peak Hours (Battery Charging)
13:      if remaining_demand  $> 0$  and total_excess_solar  $> 0$  then
14:        Divide remaining_solar equally among households
15:        energy_to_battery  $\leftarrow$  battery.charge(individual_share)
16:        battery_operation  $\leftarrow$  'Charge_House' if energy_to_battery  $> 0$ 
17:      else if remaining_demand  $> 0$  then
18:        energy_from_grid  $\leftarrow$  remaining_demand
19:        battery_operation  $\leftarrow$  'Solar_Grid'
20:      end if
21:    else if  $18 \leq \text{hour} \leq 20$  then
22:      Peak Hours (Battery Discharging)
23:      max_discharge  $\leftarrow$  min(remaining_demand, max_discharge_rate)
24:      energy_from_battery  $\leftarrow$  battery.discharge(max_discharge)
25:      remaining_demand  $\leftarrow$  remaining_demand - energy_from_battery
26:      if remaining_demand  $> 0$  then
27:        energy_from_grid  $\leftarrow$  remaining_demand
28:        battery_operation  $\leftarrow$  'Discharge_Grid_House'
29:      end if
30:    else
31:      Late Hours (Meet Demand from Solar or Grid)
32:      energy_from_school_solar  $\leftarrow$  min(household_demand,
       remaining_solar)
33:      remaining_demand  $\leftarrow$  household_demand -
       energy_from_school_solar
34:      if remaining_demand  $> 0$  then
35:        energy_from_grid  $\leftarrow$  remaining_demand
36:        battery_operation  $\leftarrow$  'Grid_House'
37:      end if
38:    end if
39:  end for
40: end for

```

by the school for later use. Algorithm 1 manages household battery charging and discharging, based on demand and time of day. Solar energy is equally distributed among households when their state of charge (SOC) falls below 99%.

2.4.5. Input and output parameters

Table 1 summarises the key input and output parameters used in the CBET simulation model. Inputs are based on empirical data and system design assumptions, while outputs represent the key metrics derived from the simulation.

2.5. Modelling assumptions and limitations

This study serves as a proof-of-concept rather than a fully generalisable deployment model. The limitations of temporal misalignment between school and household datasets could affect the magnitude of energy flows and cost savings in real-world implementations. The simulation framework prioritises relative load shapes (for dynamic

Table 1
Input and output parameters of the CBET simulation model.

Input parameters			
Parameter	Description	Unit	Source/Value
PV system size (School)	Installed solar capacity at the school	kWp	15 [33]
Battery size (School)	Battery storage capacity at school	kWh	6 [33]
Battery size (Household)	Battery storage capacity per Household	kWh	3
Household demand profiles	Household hourly energy usage	kWh	[32]
School load profile	Smart meter hourly usage data from schools	kWh	[34]
Inflation rate	Annual inflation rate for cost modelling	%	10
Project horizon	Duration for lifetime cost analysis	Years	10
Energy trading rate	Price per kWh for traded solar energy	ZAR/kWh	0.70
Input parameters			
Parameter	Description	Unit	Source/Value
Grid energy usage	Total grid energy consumed per household	kWh	Simulated output
Solar energy bought	Solar energy acquired from school	kWh	Simulated output
Peak hour demand reduction	Decrease in grid demand during peak hours	%	Simulated output
Revenue in 9 months	The school's 9-Month earnings from selling solar	ZAR	Computed value from Eq. (1)
Revenue in 10 years	The school's 10 years projected earnings from selling solar	ZAR	Computed value from Eq. (2)
Cost reduction	Reduction in household energy costs (9-Months)	%	Computed value from Eq. (3)
Lifetime savings	Net savings after investment over 10 years	%	Computed value from Eq. (4)

interaction analysis) and temporal demand patterns – such as the timing of morning and evening peaks – rather than absolute consumption magnitudes. This choice is consistent with the study's objective of evaluating system behaviour and comparative performance trends across baseline and CBET configurations, rather than predicting absolute energy demand or cost outcomes for a specific year. Nevertheless, the temporal mismatch introduces uncertainty regarding the magnitude of simulated energy flows and cost savings. The results should therefore be interpreted as indicative of directional impacts under representative demand patterns, rather than as precise forecasts of present-day household electricity consumption.

The simulation framework adopts a set of simplifying assumptions to support transparent evaluation of CBET behaviour under constrained and realistic conditions. These assumptions are explicitly stated to ensure reproducibility and to clarify the scope within which the results should be interpreted. The simulation is conducted at an hourly temporal resolution, consistent with the resolution of the empirical electricity consumption datasets used for both the school and households. Hourly time steps are sufficient to capture daily load variations, solar generation profiles, and time-of-use tariff structures, while avoiding artificial interpolation that could introduce additional uncertainty. Electricity tariffs are modelled using static TOU pricing aligned with South Africa's national grid tariff structure. Tariff values are assumed to be uniform across households and constant over the simulation period. This approach enables consistent comparison between baseline and CBET configurations while avoiding the confounding effects of dynamic pricing or market-based bidding, which are not widely implemented in low-income residential contexts. Network losses, inverter inefficiencies, and degradation effects are not explicitly modelled. This simplification is intentional and reflects the study's focus on relative system behaviour rather than absolute efficiency estimation. Excluding these factors may lead to a modest overestimation of available renewable energy and cost savings; however, their inclusion would affect all configurations similarly and would not alter the comparative performance trends observed between baseline, CBET without storage, and CBET with storage scenarios. No sensitivity analysis is conducted in this study, as the objective is to demonstrate the feasibility and directional impacts of a simplified CBET configuration rather than to optimise system parameters. Future work could extend the model to examine the sensitivity of outcomes to tariff variability, storage efficiency, and alternative temporal resolutions as CBET frameworks mature toward deployment.

3. Results and discussion

This section presents the combined results and discussion of the CBET simulation, examining system behaviour under two predefined

configurations: (1) CBET without household battery storage and (2) CBET with household battery storage. Results are discussed in relation to existing literature to contextualise observed patterns in local energy reuse, household electricity cost impacts, and peak-demand management. The analysis proceeds from the institutional prosumer (school) level to household-level outcomes, before synthesising system-level implications for equitable and circular energy system design. All results are based on nine months of simulated operation using empirical electricity demand data from a public school and low-income households in the Western Cape, South Africa.

3.1. School (Prosumer) under CBET

Table 2 presents the key metrics for solar energy utilisation by the school (prosumer) in the two configurations. We set a flat rate of 0.7 ZAR/kWh for every excess solar energy sold. The metrics provided include excess solar generated, solar sold, remaining solar, revenue generated in 9 months, and the projected revenue over 10 years with a 10% annual inflation rate. Revenue from Solar Energy R is derived from Eq. (1)

$$R = E_{\text{sold}} \times p \quad (1)$$

where: R : Total revenue generated from solar energy sales (ZAR), E_{sold} : Total amount of solar energy sold to households (kWh), p : Unit price of solar energy (0.7 ZAR/kWh). To estimate the school's total revenue from solar energy sales over 10 years, we use a growing annuity projection model. This approach is appropriate because revenue is earned annually and is assumed to increase at a constant rate (10%) due to inflation or rising energy prices. The projected Revenue over 10 Years R_{10} is calculated as:

$$R_{10} = R_{\text{annual}} \cdot \frac{(1 + g)^T - 1}{g} \quad (2)$$

where: R_{10} : Total revenue over 10 years (ZAR), R_{annual} : Annual revenue (extrapolated from 9-month value), g : Annual growth rate (10%), T : Number of years (10). The projection defined in Eq. (2) reflects the accumulated total of recurring inflation-adjusted income, not the future compound value of a single amount. The annual revenue is extrapolated from 9-month trading results and projected forward for a 10-year horizon.

Revenue in 10 years (ZAR)

In both configurations, the 15 kWp PV installation generated surplus energy beyond the school's internal demand, enabling redistribution to neighbouring households through CBET. As summarised in Table 2, the presence of household battery storage substantially improves

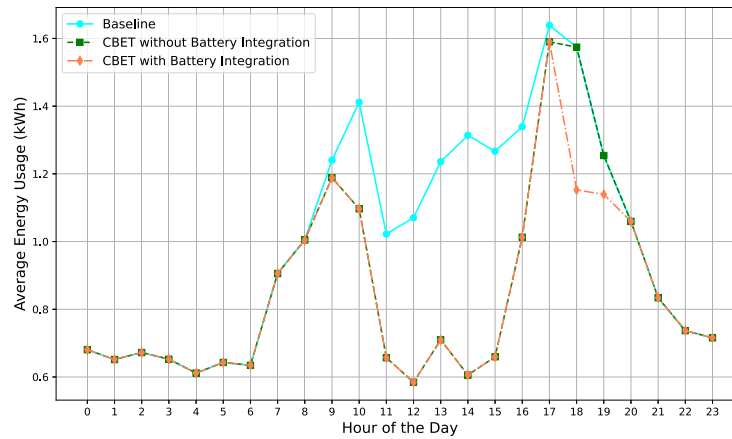


Fig. 2. Average hourly electricity consumption profile for Household 2 under three configurations: baseline grid-only supply (baseline), CBET without household battery storage, and CBET with household battery storage.

Table 2

Solar energy sales and revenue details for the school (Prosumer).

Sales/Revenue	School (Prosumer)	
	Without household battery	With household battery
Excess solar after 9 months (MWh)	5.7	5.7
Solar sold after 9 months (MWh)	4.4	5.1
Remaining solar after 9 months (MWh)	1.3	0.6
Revenue in 9 months (ZAR)	3057	3569
Revenue in 10 years (ZAR)	10 579	12 339
Efficiency of Solar Usage in 9 months (%)	77.0	89.9

the school's ability to retain surplus solar energy within the community. Battery-enabled households increase the temporal flexibility of demand, allowing a larger share of daytime solar generation to be absorbed locally rather than remaining unused. This indicates that CBET enhances local energy circularity not by increasing generation, but by improving the alignment between surplus supply and community demand.

Improved local absorption of surplus solar energy also strengthens the economic performance of the institutional prosumer. Higher local utilisation translates into increased energy sales and improved revenue trajectories over both short - and long-term, as illustrated in [Appendix B](#). These gains are achieved without dynamic pricing, market-clearing mechanisms, or bidding-based optimisation, demonstrating that meaningful financial benefits can arise from simple, rule-based energy sharing arrangements. This finding reinforces prior work showing that community-scale trading can improve the viability of institutional prosumers by monetising surplus generation that would otherwise be underutilised [19,23,24]. From a system-level perspective, improved solar utilisation at the prosumer level contributes to reduced grid interaction and smoother net load profiles. By increasing the proportion of renewable energy retained within the community, CBET reduces reliance on centralised infrastructure and supports local buffering of variability. Such outcomes are increasingly recognised as key contributors to grid resilience in regions experiencing supply instability and peak-demand stress [12,20].

Beyond technical and economic performance, the prosumer results highlight the institutional role of public schools as anchors for circular energy systems. Unlike private prosumers, schools operate within a public service mandate, where revenue generation is secondary to social value creation. By redistributing surplus energy locally, the school functions not merely as an energy producer but as an enabling node for equitable access to clean electricity. This aligns with emerging perspectives on community energy systems that emphasise shared

value creation, infrastructure reuse, and place-based governance as core elements to sustainable energy transitions [30]. This dual benefit illustrates how economic and environmental circularity can align under appropriately designed local systems. Overall, the results indicate that CBET enhances the effectiveness of institutional prosumers by increasing renewable energy utilisation, generating supplementary revenue, and reinforcing local energy circularity. The findings suggest that community-centred trading arrangements can unlock both economic and social value from decentralised generation, even in settings where advanced market mechanisms are impractical or unavailable.

3.2. Household-level impacts of CBET

Households participating in the CBET model experienced consistent reductions in grid electricity usage under both configurations, reflecting the substitution of grid supply with surplus solar energy from the school. As summarised in [Table 3](#), these reductions occur even in the absence of household-owned generation assets, demonstrating CBET's capacity to deliver affordability gains in low-income settings where individual PV investment is often infeasible. In the configuration without battery storage, grid reductions are primarily observed during daylight hours, when household demand partially overlaps with solar availability. This indicates that direct energy trading alone can improve access to low-cost electricity, but remains constrained by temporal misalignment between generation and demand. [Fig. 2](#) illustrates this dynamic for Household 2, which represents the most responsive demand profile among the sampled households. While CBET without storage reduces daytime grid reliance relative to the baseline, evening peak demand remains largely unchanged, highlighting the limitations of trading-only configurations. This outcome is consistent with widely reported challenges in decentralised energy systems where solar generation and peak demand occur at different times [35–37]. Similar patterns across other households are provided in [Appendix A](#). The introduction of household battery storage fundamentally alters this relationship. Battery-enabled households exhibit deeper reductions in grid consumption and substantially improved peak-hour demand mitigation, as shown in [Table 3](#) and [Fig. 3](#). Storage enables excess solar energy received through CBET to be temporally shifted from daytime generation periods to evening demand peaks, reducing reliance on grid electricity during periods of system stress. These findings align with existing literature demonstrating the role of distributed storage in enhancing renewable self-consumption and flattening demand profiles in community energy systems [30,38,39]. Notably, comparable outcomes are achieved here without optimisation-based or market-clearing mechanisms that assume high technological and financial readiness. The CBET model achieves comparable demand reductions through rule-based energy allocation, suggesting that meaningful resilience gains

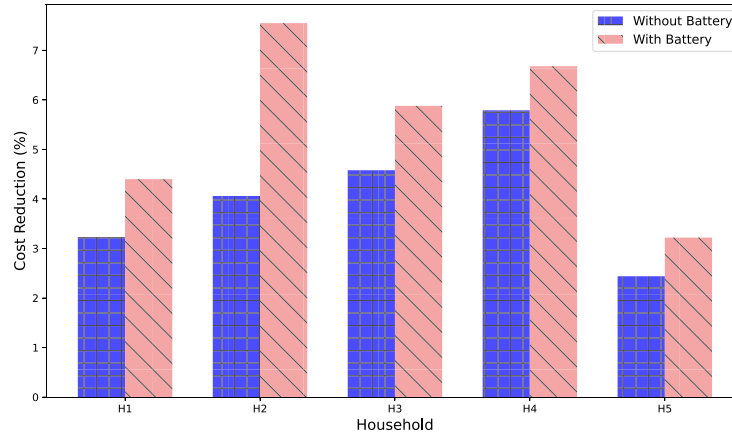


Fig. 3. Percentage reduction in household electricity costs over nine months under CBET configurations with and without battery storage.

can be realised even under simplified control strategies. This finding is particularly relevant for low-income communities, where access to advanced energy management systems is limited and infrastructural simplicity is critical for adoption [3,5,6,23,39]. Cost savings followed a similar pattern, as seen in Fig. 3. While all households benefited economically from participation in CBET, households equipped with batteries consistently achieved higher reductions in electricity costs.

Cost Reduction CR is calculated based on Eq. (3).

$$CR_{\%} = \left(\frac{C_{\text{grid}} - (C_{\text{new grid}} + C_{\text{solar}})}{C_{\text{grid}}} \right) \times 100 \quad (3)$$

where: $CR_{\%}$: Percentage cost reduction, C_{grid} : Total cost of grid electricity in the baseline scenario (without solar trading), $C_{\text{new grid}}$: Grid electricity cost after solar trading, C_{solar} : Cost of solar energy purchased from the school.

Despite these overall improvements, household-level outcomes remain sensitive to the alignment between demand profiles and predefined battery discharge schedules. Fig. 5 illustrates how fixed discharge windows can limit storage effectiveness when household peak demand falls outside the assumed evening peak period. For example, Household 3 exhibits a demand peak earlier than the battery discharge window, while Household 5 shows a predominantly morning peak, reducing the opportunity for effective grid substitution. These results reinforce prior findings that static battery dispatch strategies may underperform when household load profiles deviate from standardised assumptions [40–42]. Although adaptive battery control strategies that respond to household-specific demand patterns could further improve cost savings and peak-demand mitigation, such approaches typically require additional sensing, forecasting, or optimisation capabilities. Incorporating adaptive discharge schedules – such as shifting discharge windows toward observed morning or early-evening peaks – could enhance household-level performance, particularly for households with non-standard demand profiles. However, exploring such strategies is beyond the scope of this proof-of-concept study and represents a valuable direction for future work.

Lifetime Savings with Battery Integration LS is calculated as:

$$LS_{\%} = \left(\frac{C_{\text{no-batt}} - (I + I_{\text{battery}} + (C_{\text{no-batt}} - S))}{C_{\text{no-batt}}} \right) \times 100 \quad (4)$$

where: $LS_{\%}$: Lifetime percentage savings from battery integration, $C_{\text{no-batt}}$: Total 10-year grid cost without battery (inflation-adjusted), I : Initial battery investment cost, I_{battery} : Fixed installation cost, S : Total 10-year grid savings with battery (compounded annually).

To examine how energy trading and battery integration affect household electricity consumption across demand periods, household

energy use was aggregated according to South Africa's time-of-use (TOU) classifications — peak, off-peak, and standard. Fig. 4 presents the average hourly energy consumption for each household over the nine-month simulation period for peak and off-peak TOU. The standard period was omitted due to its similarity to off-peak results. During peak periods (Fig. 4(a)), CBET without battery storage delivers modest reductions in peak-period grid use, reflecting limited direct substitution during evening hours. In contrast, battery integration produces pronounced peak-demand reductions across households by enabling stored solar energy to be discharged during high-tariff periods. Also, off-peak consumption (Fig. 4(b)) reduces under both CBET configurations, driven primarily by direct solar utilisation during periods of high irradiance. The negligible effect of storage during off-peak periods confirms that off-peak savings are attributable to energy trading rather than battery operation.

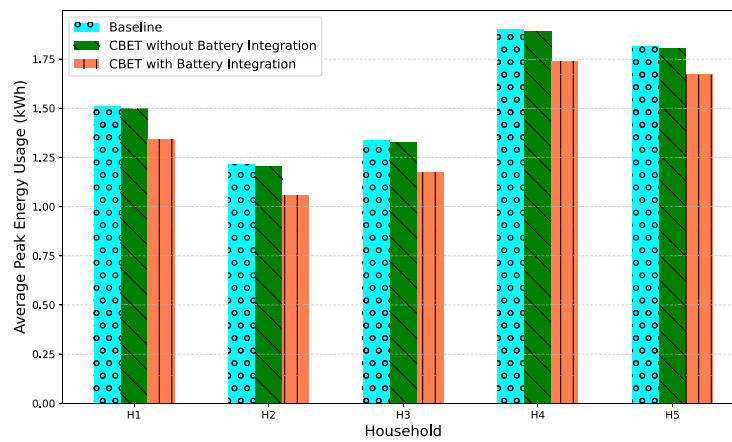
From a circular economy perspective, these household-level results demonstrate that CBET enhances the retention of renewable energy within the community by extending its temporal usability through shared access to storage. By allowing households to benefit from locally generated solar energy without owning generation assets, CBET lowers participation barriers and redistributes the value of decentralised generation more equitably. This collective-use arrangement contrasts with conventional P2P trading models that privilege asset-owning producers, reinforcing the value of community-centred approaches to circular energy transitions in under-resourced contexts.

Overall, the battery-enabled CBET configuration achieves the most effective household-level outcomes, combining improved affordability, reduced peak demand, and increased local renewable energy utilisation. These benefits reflect not only the presence of storage, but the coordination of generation, storage, and demand within a bounded community system. In this model, the school functions as a stabilising energy hub, enabling household-level resilience while simultaneously reducing stress on the wider grid. The simplicity of the one-producer-multiple-consumer structure reduces transaction complexity and infrastructure requirements, supporting operational feasibility while maintaining equitable access to clean energy. In this way, equity and simplicity reinforce circularity by minimising both economic and infrastructural inefficiencies. As a shared-access mechanism, CBET distributes the value of renewable generation without requiring high individual capital investment, creating a foundation for scalable and inclusive community energy systems. Within this model, improvements in local solar reuse, household cost savings, and peak-demand reduction represent complementary expressions of energy, socio-economic, and infrastructural circularity at the community scale. By reframing renewable energy as a shared community resource rather than a private asset, CBET provides a practical pathway toward inclusive, circular energy systems that balance technical performance with social equity.

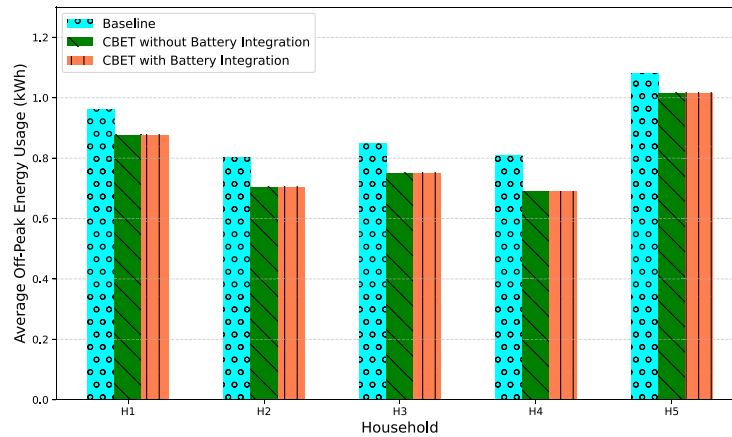
Table 3

Households: Results with and without household battery integration for nine months.

Without battery integration	H1	H2	H3	H4	H5
Baseline grid usage (MWh)	7.6	6.6	7.2	7.9	7.8
Improved grid usage (MWh)	6.9	5.7	6.2	6.8	7.2
Reduction in grid usage (%)	9.94	14.21	11.46	13.76	7.93
Reduction in energy cost (%)	3.23	4.06	4.58	5.79	2.44
Peak hour demand reduction (%)	0.74	0.72	0.74	0.58	0.43
Total solar bought (kWh)	756.33	937.82	971.08	1084.07	616.21
With battery integration	H1	H2	H3	H4	H5
Baseline grid usage (MWh)	7.6	6.6	7.2	7.9	7.8
Improved grid usage (MWh)	6.7	5.5	6.1	6.7	7.0
Reduction in grid usage (%)	11.94	16.44	15.52	15.65	9.62
Reduction in energy cost (%)	4.40	7.55	5.88	6.68	3.22
Peak hour demand reduction (%)	11.05	13.08	12.16	8.57	7.83
Solar bought for meeting demand (kWh)	756.47	756.47	971.28	1085.1	616.36
Solar bought to charge battery (kWh)	152.92	147.64	149.83	149.18	132.23
Percentage savings over the lifetime (%)	2.40	5.44	3.12	4.87	1.24



(a) Electricity usage across households for peak period for both configurations.



(b) Electricity usage across households for off-peak period for both configurations.

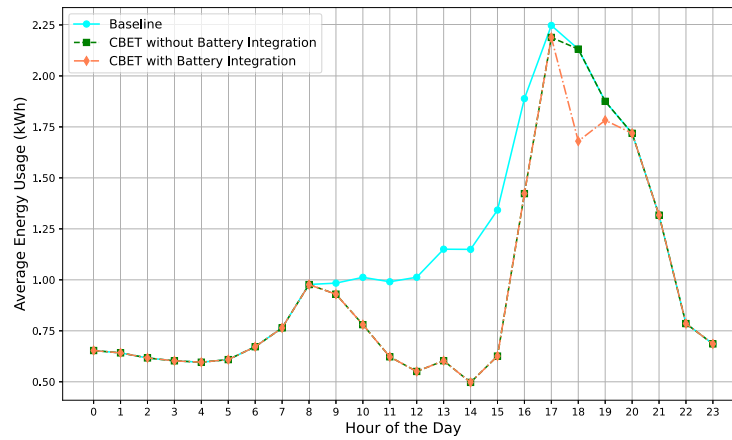
Fig. 4. Average household electricity consumption during peak and off-peak periods across baseline and CBET configurations.

3.3. Ideal system-level community-based energy trading arrangement

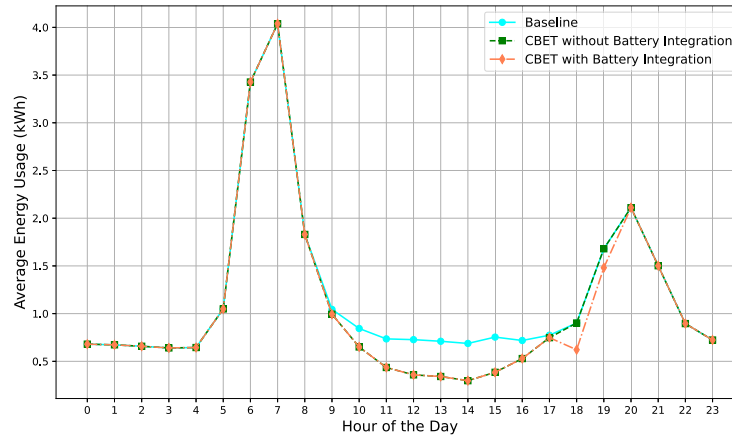
The household – and prosumer – level results indicate that the performance of CBET is shaped not only by individual components, but by the system-level coordination of generation, storage, and demand within a bounded community. This section synthesises the simulation findings into a set of *system-level design implications* that inform how CBET arrangements could be structured under different contextual and policy conditions. These considerations are forward-looking and

illustrative, and do not constitute empirically validated governance or scalability outcomes.

1. **Adaptive and Context-Aware Battery Management:** The results highlight that fixed battery discharge schedules can lead to mismatches with heterogeneous household demand profiles. This suggests that future CBET implementations could benefit from adaptive battery management strategies that align charge



(a) Average daily load profile for Household 3 with battery.



(b) Average daily load profile for Household 5 with battery.

Fig. 5. Average daily load profile for Household 3 and Household 5 with battery, illustrating the alignment (and misalignment) between household demand peaks and battery discharge schedules.

and discharge cycles with observed demand patterns, grid conditions, or TOU pricing. While not evaluated in this study, adaptive and demand-responsive battery control has been widely shown to improve the temporal alignment between renewable generation, storage, and usage in decentralised energy systems [30,37].

2. **Real-Time Monitoring for Transparent and Participatory Energy Management:** The effectiveness of community energy sharing is closely linked to transparency and user awareness. A CBET arrangement could therefore incorporate real-time monitoring interfaces that allow institutional prosumers and households to visualise energy flows, battery state, and trading interactions. Although not modelled explicitly, such transparency has been identified as an enabling condition for trust, accountability, and sustained participation in local energy markets and community energy systems [43–45].
3. **Community Incentives, Capacity Building, and Social Learning:** Beyond technical performance, the CBET framework points to the importance of social engagement in sustaining circular energy practices. Design features such as transparent reporting of savings, shared responsibility for system upkeep, and basic energy literacy initiatives could strengthen community participation and reinforce collective ownership of local energy

resources. These mechanisms align with socio-technical perspectives on energy transitions that emphasise social learning, and participation [46,47].

4. **Policy-relevant Design Considerations:** While the simulation does not assess regulatory feasibility, the CBET configuration highlights policy-relevant considerations for enabling community-based energy exchange. These include flexible feed-in arrangements, simplified procedures for institutional micro-generation, and regulatory clarity around data governance and pricing transparency. Previous studies suggest that such enabling frameworks are particularly important in low-income and resource-constrained contexts, where institutional capacity and market complexity can otherwise limit decentralised energy adoption [3,11,13,18].

The CBET model aligns strongly with the socio-economic context of this case study by providing cost-effective and inclusive access to clean energy. Households in the community, primarily consumers with limited financial capacity to install individual PV systems or storage units, benefit from the school's role as a shared prosumer. By purchasing surplus solar energy at a lower cost than grid electricity, they bypass the capital and maintenance burdens of private renewable ownership. The model also simplifies operational management by

centralising generation and trading, reducing the complexity of multi-prosumer systems while promoting transparency and energy literacy. In this way, CBET represents a transitional circular model as a bridge between conventional grid dependence and fully decentralised P2P trading frameworks. From a policy perspective, the system offers a practical and adaptive pathway for municipalities already experimenting with feed-in tariffs and decentralised generation. As highlighted across several studies [1,22,23], the success of such systems depends on regulatory innovation that ensures fairness, transaction transparency, and local empowerment. Embedding these mechanisms within the CBET framework can transform community-based trading into a cornerstone of equitable and circular energy transitions in low-income regions.

Altogether, the results demonstrate that CBET can improve energy circularity, household equity, and system resilience through simplified, rule-based coordination rather than optimisation-driven control. Across prosumer, household, and system levels, CBET consistently retains renewable energy within the community while reducing peak-period grid dependence. These findings provide a foundation for considering CBET not only as a technical intervention but as a scalable design framework for inclusive decentralised energy systems.

4. Conclusion and future work

This study presented a simulation-based assessment of a Community-Based Energy Trading (CBET) model as a context-sensitive framework for advancing energy circularity within under-resourced settings. By modelling a solar-powered school as a single institutional prosumer that redistributes surplus renewable energy to nearby low-income households, the analysis illustrates how existing social infrastructure can support local energy looping and shared access to clean electricity. The simulation results indicate that, under the assumed conditions, community-level energy trading combined with household battery storage is associated with a 16% reduction in grid dependency, a 13% reduction in peak-hour demand, and a 17% increase in local renewable energy reuse. These outcomes suggest that simplified community energy sharing arrangements can deliver meaningful techno-economic and system-level benefits without requiring household-level PV ownership.

From a policy perspective, the CBET configuration highlights a set of design-relevant considerations for enabling circular energy systems in low-income contexts. South Africa's evolving municipal frameworks for embedded generation, particularly in the Western Cape, provide an institutional backdrop that may support experimental community-based energy arrangements. However, the present study does not evaluate regulatory feasibility or governance readiness. Rather, the findings indicate that flexible regulatory mechanisms, simplified institutional participation, and context-aware governance structures could be important in enabling conditions for future CBET implementations. More broadly, the study contributes to discussions on circular economy applications in the Global South by illustrating how circularity in energy systems may emerge as a context-dependent process, shaped by local infrastructure, demand patterns, and institutional capacity rather than by a universal system design.

Several limitations of the study should be acknowledged. The simulation relies on electricity consumption data from different time periods for schools and households, which may affect temporal alignment and the magnitude of estimated impacts. Household classifications are based on consumption proxies due to the absence of location-specific socio-economic data, introducing simplifying assumptions. In addition, the analysis focuses on a single community configuration, which limits broader generalisation but strengthens the contextual relevance of the findings. From a technical perspective, the use of a static battery discharge schedule constrains storage performance for households with non-aligned demand peaks.

Future research should therefore extend the CBET framework along both technical and socio-institutional dimensions. Incorporating adaptive battery control or demand-side management strategies could improve alignment between household demand and renewable generation, while expanding the model to include multiple institutional prosumers – such as clinics, community centres, or small enterprises – could explore networked community energy configurations. Empirical pilot studies would be particularly valuable for validating behavioural responses, operational reliability, and governance arrangements under real-world conditions. Further exploration of reciprocal energy sharing, including decentralised battery contributions from households to public institutions during peak or supply-constrained periods, may also offer insights into more resilient and socially embedded circular energy systems.

In conclusion, achieving equitable low-carbon futures in developing regions requires more than technology deployment; it demands context-sensitive systems that close resource loops, democratise access, and regenerate social and economic value within communities. The CBET framework provides a conceptually replicable pathway for building such systems, placing equity, participation, and regional reality at the centre of the sustainability agenda. Advancing CBET calls for an integrated, multidisciplinary approach that aligns technology, policy, and social innovation, thereby accelerating the transition toward equitable and resilient circular energy ecosystems. Overall, the study provides evidence that achieving equitable low-carbon transitions in developing regions requires more than technology deployment alone. Simulation-based evidence from this work suggests that context-sensitive, community-oriented energy sharing arrangements can support circular energy objectives by retaining renewable value locally and broadening access to clean energy services. Advancing CBET will require continued integration of technical modelling, institutional experimentation, and policy learning to ensure that community-led circular energy systems evolve in ways that reflect local realities and capacities.

CRedit authorship contribution statement

T. Michael-Ahile: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.A. Samuels:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **M.J. Booysen:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Comparative performance of battery-enabled households and non-battery-enabled households

This appendix provides charts for each of the five households, comparing energy metrics with and without battery integration (see Figs. A.6–A.10).

Appendix B. Prosumer projected revenue growth over 10 years with and without battery configurations

See Fig. B.11.

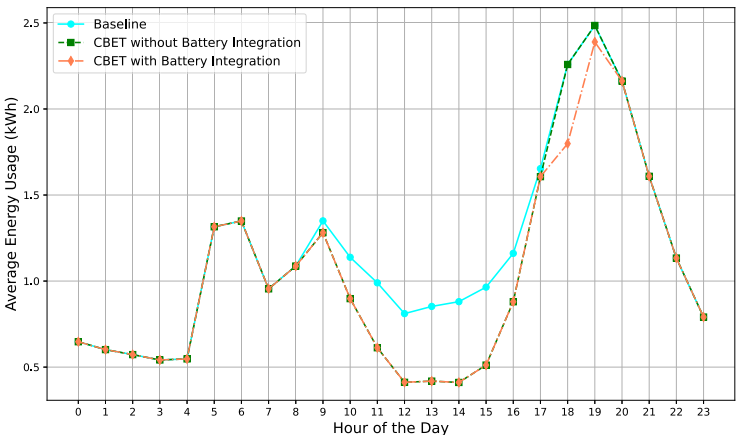


Fig. A.6. Average hourly electricity consumption for Household 1 comparing baseline grid-only operation with CBET configurations with and without battery storage.

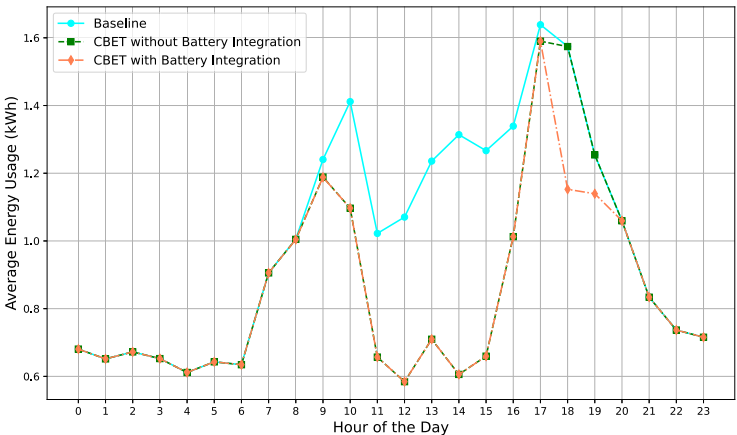


Fig. A.7. Average hourly electricity consumption for Household 2 comparing baseline grid-only operation with CBET configurations with and without battery storage.

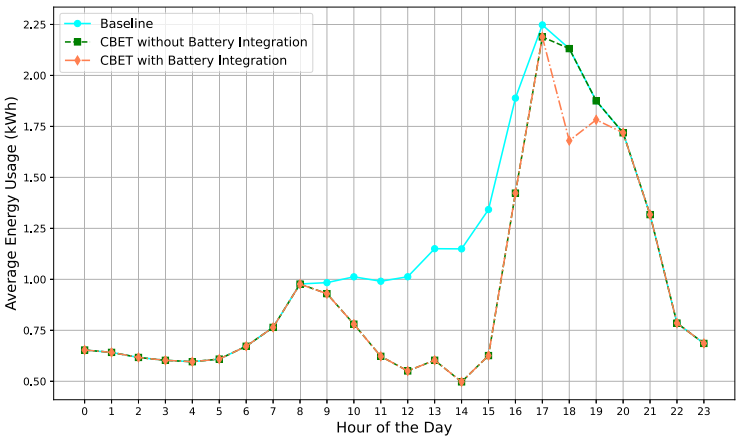


Fig. A.8. Average hourly electricity consumption for Household 3 comparing baseline grid-only operation with CBET configurations with and without battery storage.

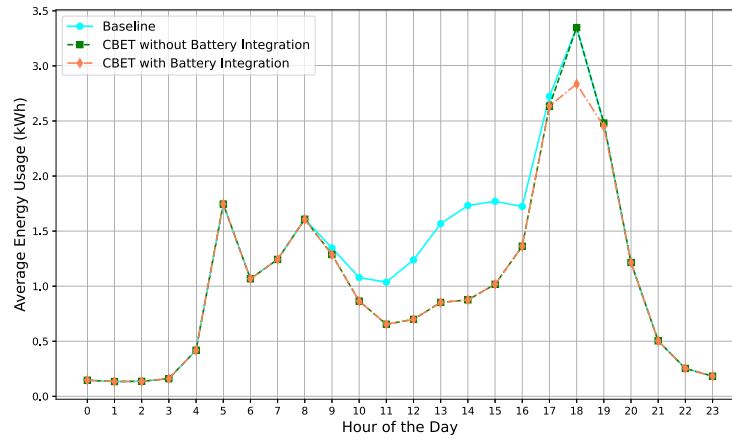


Fig. A.9. Average hourly electricity consumption for Household 4 comparing baseline grid-only operation with CBET configurations with and without battery storage.

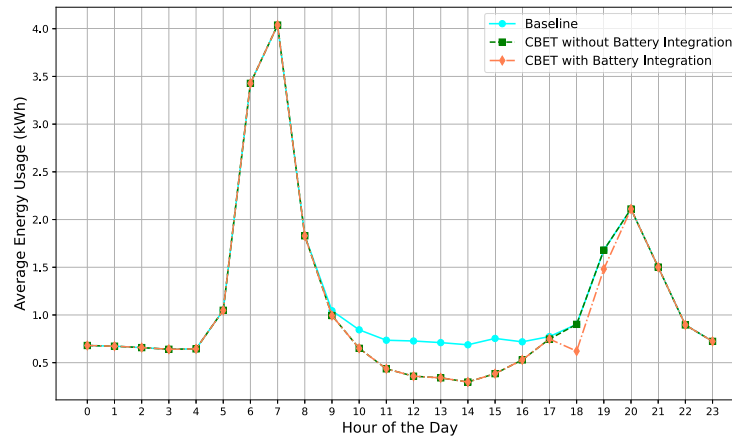


Fig. A.10. Average hourly electricity consumption for Household 5 comparing baseline grid-only operation with CBET configurations with and without battery storage.

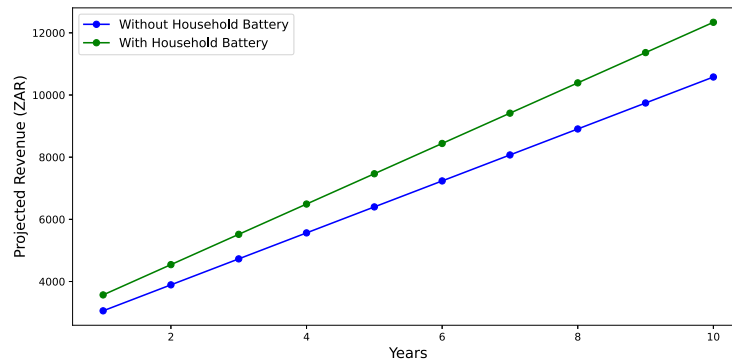


Fig. B.11. Prosumer projected revenue growth over 10 years.

Data availability

The school data that support the findings of this study are available in Mendeley Data at <http://dx.doi.org/10.17632/nm2vc4v2br.1> [31, 34]. The dataset is openly accessible under the CC BY 4.0 license.

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